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EXPERIMENTAL RESEARCH ON CURING SELF-COMPACTING CONCRETE WITH CURING COMPOUND

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ABSTRACT: The article presents the results of an experimental study on curing self-compacting concrete with a curing compound. The experiment was carried out under two natural weather conditions: hot and dry (summer) and hot and humid (autumn), in the Hanoi area. To evaluate the effectiveness of the curing method with a curing compound, three main aspects were studied: plastic shrinkage, water evaporation, and compressive strength of the samples. The experiment was conducted with three methods: (i) using a curing compound, (ii) using water spraying and (iii) no curing. The experiments showed that the sample cured with a curing compound has the smallest plastic shrinkage, corresponding to 0.67mm/m in hot dry conditions and 0.37mm/m in hot humid condition. In addition, the sample cured with a curing compound also has the smallest rate of water evaporation, corresponding to 12.7% and 5.12% in hot and dry, and hot and humid conditions respectively. At the same time, the self-compacting concrete sample cured with a curing compound has the best R^{28} sample compressive strength value, reaching 101.4% R^{28}_{tc} in hot and dry conditions and 100.9% R^{28}_{tc} in hot and humid conditions. These results, thereby, have proved the effectiveness of the curing method with a curing compound for self-compacting concrete under Vietnamese weather conditions.

Keywords: Self-compacting concrete, Curing compound, Curing

1. INTRODUCTION

Self-compacting concrete (SCC) is a special type of concrete with high consistency and good workability. The concrete mixture can flow through the corners of the main formwork by its own gravity without the need for vibration force while ensuring strong compactness [1]. The composition of the SCC mixture differs from conventional concrete in several ways, including a higher content of powder, a higher amount of superplasticizer admixture, a smaller amount of coarse aggregate, and a lower water-to-powder ratio (W/P). Therefore, the behavior of SCC in the early hardening stage, in particular, water evaporation and plastic shrinkage, will be different from conventional concrete, leading to more specific cure work for SCC.

So far, there have been many studies worldwide regarding the curing method of SCC using curing compounds,, specifically: LA Qureshi's study [2] showed that the strength of water-cured concrete at the construction site reached 89% of the strength of samples cured by immersion in water, while the strength of concrete cured by curing compounds only reached 90-93% compared to the strength of samples cured by immersion in water. In another study by Hajime Okamura [3], it was found that the method of surface coating using curing compounds had the effect of limiting cracks due to plastic shrinkage. Another research from Akanksha [4] showed that the use of curing compounds did not significantly affect the durability of concrete and that traditional water curing was proven to be quite expensive due to the increasingly scarce and expensive water resources. A survey at Texas University [5] on R28 concrete samples with strengths ranging from 41-100 MPa showed that fly ash accounted for 25%-35% of the volume of powder with different curing conditions: standard curing (in a humid room), using curing compounds (ambient temperature of 27-38°C, humidity of 30-60%), and no curing. The results showed that at 15 days of age, the compressive strength of the samples cured with curing compounds was higher than those cured in a humid room by about 3%. However, at 56-91 days of age, the compressive strength of the samples cured in a humid room was higher than those cured with curing compounds. Senbetta's study [6] showed that different curing methods affect the durability of SCC, such as resistance to abrasion, steel corrosion, chloride penetration, absorption, and shrinkage. Concrete cured with paraffin had good durability. Proper curing practices can improve durability by up to 50% compared to uncured, significantly reducing shrinkage and cracking, and reducing air voids by up to 80%. Tiznobaik's study [7] on the construction of a concrete road has shown that applying a thorough coat of curing compound is essential to ensure moisture retention in the concrete, which is necessary for efficient hydration reactions and microstructural development.

While there are so many studies on this area, to date, there is no specific standard for self-compacting concrete (SCC)'s curing in Vietnam and globally, which makes it difficult to choose a suitable method, especially under Vietnam's climate conditions. Furthermore, it is acknowledged that the above listed studies were conducted in different conditions compared with the climate conditions of Vietnam (for eg: laboratory settings with controlled temperature and humidity conditions or different climate conditions).

In this study, we conducted experimental research on the curing method of self-compacting concrete (SCC) using curing compounds, focusing on aspects such as plastic shrinkage, water evaporation, and compressive strength of SCC under hot and dry as well as hot and humid climate conditions in the Hanoi area. The effectiveness of the curing method using curing compounds was evaluated in terms of reducing water evaporation, minimizing plastic shrinkage, and ensuring the compressive strength of SCC compared to the water spraying curing and no curing methods.

2. RESEARCH SIGNIFICANCE

Traditional curing methods have shown limitation when the curing are required for tall structures, inaccessible areas, or water-scarce areas. Moreover, in reality, water spraying method is not always perfectly implemented (the number of times and days of spraying are often reduced by contractors), leading to the inefficiency of this traditional cure method. The curing method using curing compounds can address the aforementioned drawbacks. In addition, curing with curing compounds has significant environmental benefits since the process does not generate non-degradable waste and does not consume any water.

The research on curing method by curing compound is, therefore, critical for the application of SCC in Vietnam to become more popular.

3. SELF-CURING METHOD OF SELF-COMPACTING CONCRETE WITH CURING COMPOUND

According to [8], curing concrete is the process of keeping the concrete moist regularly under the influence of local climate factors by (i) directly spraying water onto the concrete surface, or (ii) covering the material with wet coverings, watering, and misting, or (iii) covering the concrete surface with waterproof materials. Concrete, immediately after being poured, needs to be covered with moist materials (over any exposed surfaces) or covered with waterproof materials such as nylon, tarpaulin, or sprayed with an anti-evaporation membrane. Self-curing of concrete is a method of maintaining moisture in concrete by adding curing admixtures or curing compounds [4].

In the self-curing method, when the curing compound is sprayed onto the surface of the concrete structure, a thin crystalline film will be formed by the solidification of the compounds, which will help slow down the evaporation of water from the concrete structure, and thereby facilitating the complete hydration of the cement.

Currently, in Vietnam, there are two commonly used types of concrete curing compounds produced by Sika, namely Antisol E and Antisol S. Antisol E is a white liquid solution based on paraffin resin-emulsion. It is normally used for curing concrete surfaces that do not require further surface treatment, such as highways, airports, parking lots, and retaining walls. The other curing compound type, Antisol S compound, is used for curing vertical structural surfaces because the liquid membrane of the resin (Antisol E compound) is not suitable for unclear decomposition and thereby affects the performance of subsequent steps in the construction process. Curing compounds are applied by direct brushing or spraying onto the concrete surface after water separation processes are completely finished. When being used for column or beam structures, compounds are sprayed onto the surface after removing the formwork. Fig.1 illustrates the application of concrete curing compounds.

Fig.1 Application of concrete structure curing compound

4. EXPERIMENTAL MATERIALS, MIX PROPRTIONS, AND CLIMATIC CONDITIONS

4.1 Experimental Materials

Materials used in the experiment: Vincem But Son PC40 cement; SongHong yellow sand with a modulus of 2.76; Crushed stone with a maximum diameter of 10mm, made from crushed stone with a density of 2.67g/cm^3; Pha Lai thermal power plant fly ash, type F according to ASTM C618; Superplasticizer admixture: BiFi-HV298, a new generation polymer-based additive with a density of 1.05, compliant with ASTM C-494 type G; VMA Viscosity-modifying admixture: CuLminal MHPC400, a viscosity-increasing additive; Cure compound: Sika Atisol E type A1 according to ASTM C309, with a volume density of 0.98kg/liter and coverage of 4-6m^2/liter.

4.2 Experimental Mix Proportions and Experiment Conditions

The experimental mix design was conducted based on the experience and actual research in Japan and Europe, using the method of design recommended by the Japan Society of Civil Engineers (JSCE) and EFNARC (UK). The self-compacting concrete mixture was designed to achieve a strength level of B45, with the material components shown in Table 1.

The experiment was conducted under natural conditions in Hanoi area, and the weather conditions are shown in Table 2.

5. EXPERIMENT RESULTS

5.1 Assessing the Workability of Self-Compacting Concrete

The workability of the SCC mixture was evaluated according to TCVN 12209:2018 standard [9], with the following parameters tested: slum-flow test (SF), T500, J-ring test, L-box test, V-funnel test, and sieve segregation resistance test (SR). The results of the SCC mixture workability testing were as follows: SF=660mm; T500=3 seconds; J-ring=8mm; L-box=0.85; V-funnel=8.2 seconds; SR=7.5%. According to [10], SF values of 650-800mm, T500 of 2-5s, J-ring of 0-10mm, L-box of 0.8-1, V-funnel of 6-12s, and SR values of 5-15% are allowed. The results indicate that the workability of the SCC mix meets the minimum requirements according to European guidelines.

5.2 Test Results of Plastic Shrinkage in Self-Compacting Concrete

5.2.1 Experimental diagram

Plastic shrinkage is a physical process that occurs in the initial stage when concrete starts to set and gets hardened. Plastic shrinkage occurs after a few hours after concrete mixing due to the rapid evaporation of water, which increases negative pressure in the capillaries and pull the aggregate particles closer together, causing shrinkage in the concrete. In the study, plastic shrinkage was determined through 2 strain gauges with an accuracy of 0.002mm placed at both ends of the concrete sample size 10x10x30cm. Each end has a 0.5mm thin steel plate of 9.5x9.5cm which is attached to the concrete sample by welding more steel antennas.

The steel plate is placed and fixed prior to concrete being poured into the shrinkage gauge mold so that the outer surface of the steel plate is at the outermost boundary of the shrinkage gauge specimen. The probe needle is placed in contact with the outside boundary of the measuring plate and is adjusted to its center. When the concrete shrinks, the steel plate moves along, leading to the displacement of the measuring head. The SCC plastic shrinkage measurement diagram is shown in Fig.2.

The time to remove the mold to install the shrinkage gauge is 2 hours after pouring concrete into the measuring mold. The measuring die is lubricated with grease and lined with a layer of nylon to stabilize the specimen after removing the side panels. The measurement cycle is one hour, and we have 10 consecutive measurements within 10 hours from the start. During the measurement, the measuring table is fixed in one position, ensuring that it is not affected by vibrations from the environment. Before the first measurement, the meter is adjusted to the index 0. The value of concrete plastic shrinkage is the sum of the results of the two gauges.

Table 1 Mixture composition used in the experiment

Ciment (kg)	Fly ash (kg)	Stone (kg)	Sand (kg)	Water (kg)	Superplasticizer (kg)	VMA (kg)
449.9	147.4	770	808	185.9	5.92	0.2

Table 2 The parameters of the experimental environmental weather conditions used in the curing process of the self-compacting concrete

Weather conditions	Season	Temp (^{o}C)	Humidity (%)	Wind speed (m/s)
Hot and humid	Autumn	28-35	65-85	1-2.5
Hot and dry	Summer	28-40	40-65	1-2.5

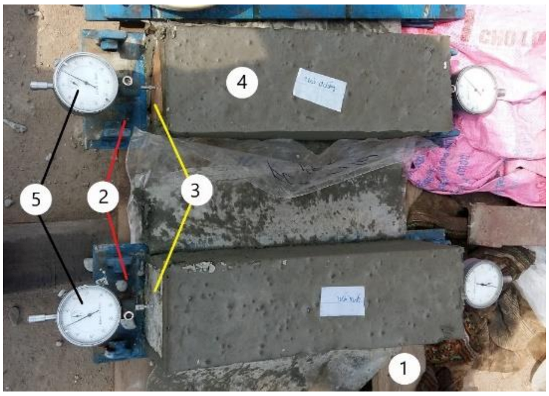

Fig.2 Measurement of Plastic Shrinkage of SCC
1-measuring table; 2-formwork bottom plate; 3-plate metal; 4-sample concrete; 5-strain gauge.

5.2.2 Experiment results

The concrete was mixed and poured into the mixing chute before being poured into the shrinkage measuring mold. Strain data was recorded every hour for 10 hours since the pouring start. The experiment results were measured, recorded in tables, processed, and presented in graphs. The plastic shrinkage measured by the meter was converted into units of mm/m length of concrete.

Under hot and dry conditions (summer): Experiment results show that the process of plastic shrinkage in concrete is concentrated in the first 6-7 hours after mixing, regardless of the curing method used. Therefore, in hot and dry conditions, the process of plastic shrinkage is considered to end after 6 to 7 hours. The curing compound curing sample (CC) showed the smallest plastic shrinkage with 0.67mm/m at the time being 10 hours after pouring, followed by the curing water spraying sample (CWS) with 2.15mm/m, and the largest plastic shrinkage occurred in the uncured sample (UC) with 2.37mm/m (refer to Fig.3).

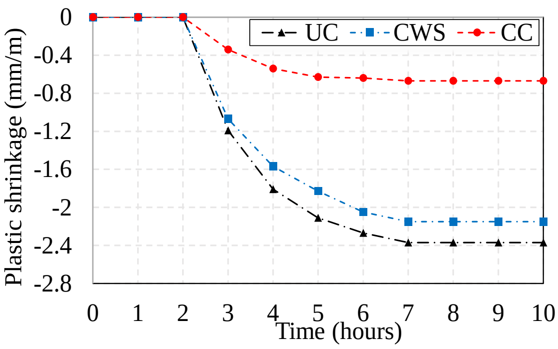

Fig.3 SCC plastic shrinkage in hot and dry conditions (summer)
The origin point (0,0) represents the end of the concrete pouring process: UC - uncured sample; CWS - curing water spraying sample; CC - curing compound curing sample.

Thus, in hot and dry climate conditions (summer) and grading as in table 1, the curing compound method is the most effective method in limiting plastic shrinkage in the early curing stage of concrete.

Under hot and humid conditions (autumn): Experiment results show that the process of plastic shrinkage in concrete is concentrated in the first 6-7 hours after mixing, regardless of the curing method used. Therefore, the plastic shrinkage process is considered to end after 6 to 7 hours. Among the three curing methods, the sample cured with compound (CC) showed the least plastic shrinkage at 0.37mm/m, at 10 hours after pouring. This was followed by the curing water spraying sample (CWS) with 1.18mm/m and plastic deformation, while the uncured sample (UC) showed the largest plastic shrinkage at 1.46mm/m (Fig.4).

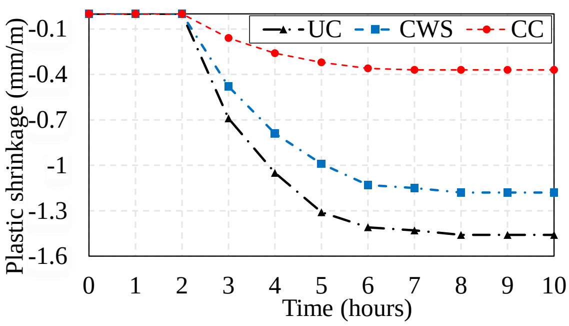

Fig.4 SCC plastic shrinkage in hot and humid conditions (autumn)
The origin (0,0) represents the end of the concrete pouring process: UC - uncured sample; CWS - curing water spraying sample; CC - curing compound curing sample

Thus, in hot and humid climate conditions (autumn) and grading as in table 1, the curing compound method is the most effective method in limiting plastic shrinkage in the early curing stage of concrete.

The water spraying-curing method, although resulting in a smaller plastic shrinkage than the non-curing method, still yields much higher shrinkage compared to the curing compound method. In addition, according to [11], when spraying water on to the concrete surface, the water on the surface will evaporate quickly, especially under hot weather conditions. In high-temperature conditions, the concrete surface is being heated, water spraying on the surface will cause thermal shock and temperature differences between the concrete regions in the cycle, and if in a short time, it can lead to concrete cracking due to thermal expansion, which in turn, will adversely affect the structure and mechanical properties of the concrete.

5.3 Experiment Results of Water Evaporation Measurement in SCC

5.3.1 Experimental diagram

The concrete's water loss process is called water evaporation (in free form, not bound in the bonds with particles and phases of the concrete setting process) into the surrounding environment under the influence of weather factors, mainly air temperature, relative humidity, wind speed, and solar radiation. The water loss process of concrete is also known as the exchange process between concrete and the external environment. The process of water evaporation occurs quickly in the initial stage of setting, mainly concentrated in the first 8-10 hours of the concrete setting process and then lasts for several days, but at a very slow rate.

To investigate the correlation between water evaporation and plastic shrinkage, measurements of both parameters were conducted in parallel. The water evaporation experiment involved weighing 10x10x30cm concrete samples on an electronic balance with an accuracy of 0.1g. Every hour, the samples were weighed and the results were recorded for the first 10 hours after pouring. Fig.5 illustrates the method used for measuring SCC water evaporative.

Fig.5 Illustrates the process of measuring the water loss of concrete

1-Electronic scales; 2-mold concrete; 3-sample concrete; 4-time meter

In hot and humid climate conditions of Vietnam, temperature, humidity, solar radiation intensity are major factors affecting the water evaporation process. In addition, the structure's uncovered surface modulus M_h (determined by the ratio of the evaporation area to the volume of the concrete block) also has a significant effect on the water evaporation process [12].

Therefore, the experimental results in this study are only applicable to conventional concrete structures and not applicable to large block concrete structures.

5.3.2 Experiment results

The process begins with mixing the concrete and pouring it into the mixing chute before transferring it to the evaporator mold. The samples were weighed every hour using an electronic balance and recorded for up to 10 hours after pouring. The experiment results were converted into tables and presented as graphs. The amount of water evaporation was expressed as a percentage of the initial water use.

Under hot and dry conditions (summer): Experiment results show that the majority of water evaporation in concrete occurred within the first 6-7 hours after mixing. Although there was continued evaporation afterward, this was minimal. Thus, in hot and dry conditions, the evaporation process can be considered to end within the first 6 to 7 hours.

The curing compound (CC) method resulted in the least amount of water evaporation, followed by the curing water spraying (CWS) method. The uncured sample (UC) had the highest amount of water evaporation. After 10 hours from the start of concrete pouring, the curing compound (CC) sample had 12.7% of the water evaporated, while the evaporative curing water spraying sample was 30.1% and the uncured sample had the highest at 32.3% (Fig.6). Thus, under hot and dry climate conditions, the curing compound (CC) method is the most effective at limiting water evaporation during the early curing stage of SCC.

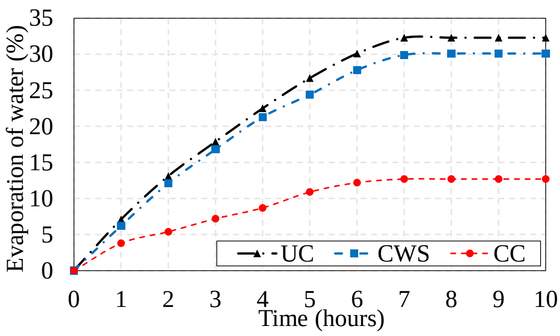

Fig.6 Evaporation of water in the first stage of SCC in hot and dry conditions

The origin point (0,0) is the end of the concrete pouring process: UC - uncured sample; CWS - curing water spraying sample; CC - curing compound curing sample

Under hot and humid conditions (autumn): Experiment results show that the majority of water evaporation in concrete occurred within the first 6-7 hours after mixing. Although there was continued evaporation afterward, this was minimal. Thus, in hot and humid weather, the evaporation process can be considered to end within the first 6-7 hours.

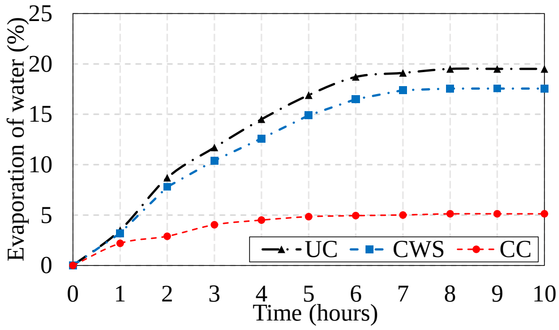

Fig.7 Evaporation of water in the first stage of SCC in hot and humid weather

The origin point (0,0) is the end of the concrete pouring process: UC - uncured sample; CWS - curing water spraying sample; CC - curing compound curing sample.

The curing compound (CC) method resulted in the least amount of water evaporation, followed by the curing water spraying (CWS) method. The uncured sample (UC) had the highest amount of water evaporation. After 10 hours from the start of concrete pouring, the curing compound (CC) sample had 5.12% of the water evaporated, while the evaporative curing water spraying sample was 17.56% and the uncured sample reached the highest at 19.5% (Fig.7). Thus, under hot and humid climate conditions, the curing compound (CC) method is the most effective at limiting water evaporation during the early curing stage of SCC.

5.4 The Experiment Results Determine the Compressive Strength of SCC

5.4.1 Experimental diagram

In order to investigate the correlation between plastic shrinkage, water evaporation, and the development of SCC compressive strength, compression tests were conducted simultaneously with plastic shrinkage and water evaporation. The compression tests were carried out under two conditions: hot and dry and hot and humid.

Concrete was mixed in batches for the purpose of measuring plastic shrinkage and water evaporation. The concrete was then molded and cured using different methods. After 28 days, the samples were compressed to determine their strength (R^{28}). Fig.8 illustrates the casting of the samples, while Fig.9 shows the compression of the SCC specimens at 28 days old.

Control specimens were cast simultaneously with the test specimens, cured under standard conditions for the first day, and then immersed in water from the second day. They were compressed at the age of 28 days to determine the standard compressive strength (R^{28}_{tc}) in two experimental conditions with different weather conditions.

Fig.8 Casting samples to determine strength (R^{28})

Fig.9 Compression of samples to determine strength

5.4.2 Experiment results

The process of making concrete involves mixing the ingredients and pouring them into a mold, which is then cured using one of four methods: Standard curing (SC), uncured (UC), curing with water spraying (CWS), and with curing compound (CC). After 28 days, each group of three samples was compressed and their strength was recorded. The results are displayed in Fig.10.

The experimental findings show that in various weather conditions, the 28-day compressive strength of concrete samples treated with curing compound (CC) was the highest, almost equivalent to the standard curing sample strength. Curing water spraying (CWS) was the next most effective, while uncured (UC) resulted in the weakest strength. The compressive strength R^{28} of the samples CC, CWS, and UC are respectively: under hot and dry conditions: 575.2 daN/cm^2 reached 101.4%R^{28}_{tc}; 545.7daN/cm^2 reached 96.2%R^{28}_{tc}; 509.1 daN/cm^2 reached 89.7%R^{28}_{tc}. Under hot and humid: 576.3 daN/cm^2 reached 100.9 %R^{28}_{tc}; 552.3daN/cm^2 reached 96.7%R^{28}_{tc}; 522.3 daN/cm^2 reached 91.4%R^{28}_{tc}.

The UC samples had the weakest compressive strength, achieving only 89.7%R^{28}_{tc} in hot and dry conditions, and 91.4%R^{28}_{tc} in hot and humid conditions. This can be explained by the significant water loss, which resulted in an inadequate amount of remaining water to facilitate a favorable hydration process, and also promoted the formation of more voids, pores, and possibly structural cracks, leading to a reduction in the concrete's compressive strength.

The results indicate that curing compound is the most effective method for achieving the highest compressive strength of concrete, regardless of weather conditions, as the R_{28} of the cured concrete samples always reached R^{28}_{tc} (101.4% và 100.9%). On the other hand, curing using water spraying (CWS) concrete did not achieve the R^{28}_{tc} (96.2% và 96.7%). This may be explained by the fact that SCC has a low W/P ratio (W/P<0.45). According to [13], with smooth and small voids, the capillaries will be disrupted after 1-3 days, so watering to supply moisture inside the concrete is not feasible, combined with a high rate of water evaporation and loss, leading to insufficient water for the hydration process, affecting the compressive strength of concrete.

In both climatic conditions, the curing method using a curing compound is the one that provides the highest compressive strength for the sample. This demonstrates that the curing method using a curing compound is the most effective way to cure SCC. When combined with the results of the water evaporation test and plastic shrinkage, we can observe a trend in which the curing method using curing compound offers the smallest plastic shrinkage, lowest water evaporation, and highest compressive strength. This indicates that the curing method using curing compound has created the most suitable temperature and humidity environment for the development of concrete strength.

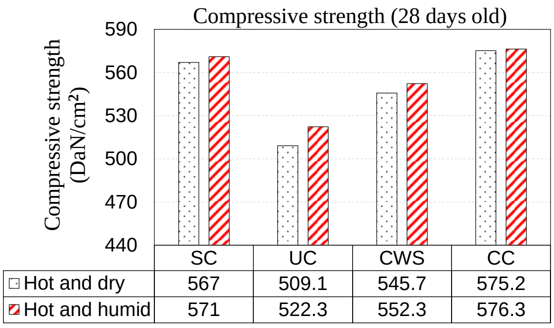

Fig.10 The compressive strength of SCC (R^{28}) in different conditions and curing

SC - Standard curing concrete sample; UC - Uncured concrete sample; CWS – Curing water spraying concrete samples; CC – Concrete specimen cured with compound

According to [14, 15], the evaporation of water from conventional concrete within the range of 30-35% of the amount of water used will not have a negative impact on its structure and quality. However, based on the compressive strength test results and water evaporation, it can be seen that this is no longer true for SCC. The limited evaporation value derived from the evaporation of the curing compound curing sample is around 13%. This might come from the fact that the amount of cementitious materials, such as powder, in SCC is much higher than in CC. Therefore, SCC needs to maintain a larger amount of water to ensure the hydration process. However, further studies with a larger number of samples are needed to accurately determine an acceptable water evaporation rate which do not affect the structure and quality of SCC.

6. CONCLUSIONS

The plastic shrinkage of SCC mainly occurs in the first 6-7 hours in hot and dry conditions (summer) as well as in hot and humid conditions (autumn) after concrete mixing. This shrinkage process continues afterwards but at a small and almost negligible rate.

Plastic shrinkage occurred with the curing method using curing compound is the smallest (among the research methods). In hot and dry conditions (summer), the plastic shrinkage in the curing with water spraying sample is 2.15mm/m, while with the curing method using curing compound, it is 0.67mm/m, corresponding to a decrease of ~68.8%. In hot and humid conditions (autumn), the plastic shrinkage in the curing with water spraying sample is 1.18mm/m, while with the curing method using curing compound, it is 0.37mm/m, a decrease of ~68.6%.

The water evaporation process in SCC occurs right after the concrete pouring, with the majority of evaporation taking place within the first 6-7 hours after pouring under hot and dry (summer) or hot and humid (autumn) conditions. The evaporation process continues thereafter, but the amount of evaporation is negligible.

Water evaporation occurred with the curing method using curing compound is the smallest (among the research methods). In hot and dry conditions (summer), the water evaporation in the curing with water spraying sample is 30.1%, while with the curing method using curing compound, it is 12.7%, corresponding to a decrease of ~57.8%. In hot and humid conditions (autumn), the water evaporation in the specimens sprayed with water was 17.56%, while that in the specimens cured with curing compound was 5.12%, corresponding to a reduction of ~70.8%.

Compared to hot and humid conditions, the plastic shrinkage and water evaporation of SCC are much greater in hot and dry conditions. Therefore, the curing process should be particularly considered during construction in hot and dry conditions. Whether in hot and dry or hot and humid conditions, the curing method is an effective way to limit water evaporation and early plastic shrinkage of SCC.

The curing method using curing compound for the concrete sample with the highest compressive strength achieved the standard strength of the sample. In hot and dry conditions, the compressive strength R^{28} has a value of 575.2 daN/cm^2 reaching 101.4% R^{28}_{tc}, while in hot and humid conditions, R^{28} has a value of 576.3 daN/cm^2 reaching 100.9% R^{28}_{tc}. Therefore, it is shown that the curing method using curing compound is an effective method for curing SCC. Combined with the results of the experiment on water evaporation and plastic shrinkage, we can see a pattern that the curing method using curing compound provides the lowest plastic shrinkage, the lowest water evaporation, and the highest compressive strength. This demonstrates that the curing method using a curing compound has created the most suitable thermal-moisture environment for the development of the concrete's compressive strength.

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